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Neck Torque Study Induced by Head-Borne Visual Augmentation Systems (VAS) in Ground-Based Applications

Version V1.2

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Contributors:
Emily Ward
Quang Luong

POC:
Matthew G. Bevan
Phone: 240-228-8944
Email: Matthew.Bevan@jhuapl.edu

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Bevan, Matthew G; Ward, Emily; Luong, Quang

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14. ABSTRACT

While providing a critical capability to conduct missions under the cover of darkness, Night Vision Goggles (NVG) are a recognized source of acute and chronic neck injuries . US Army Night Vision & Electronic Sensors Directorate and the Naval Surface Warfare Center needed to characterize the mass, Center of Gravity (CG) and neck torque generated by existing NVG and Visual Augmentation Systems (VAS) in order to understand the potential for neck pain and injury created by existing systems and provide insight on the mass and CG properties needed for future systems. NVG use light intensifier tubes to amplify existing light while VAS incorporate both light intensifiers and infra-red thermal imagers. (For the purposes of this report, NVG systems are a sub-set of VAS.) This project had three tasks:

1. Develop a method to measure the mass and CG of VAS.
2. Measure the mass and CG of seven (7) VAS and their associated mounts: AN/PVS-7D, AN/PVS-14, AN/PVS-15A, AN/PVS-23

15. SUBJECT TERMS

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1. Executive Summary

While providing a critical capability to conduct missions under the cover of darkness, Night Vision Goggles (NVG) are a recognized source of acute and chronic neck injuries[1]. US Army Night Vision & Electronic Sensors Directorate and the Naval Surface Warfare Center needed to characterize the mass, Center of Gravity (CG) and neck torque generated by existing NVG and Visual Augmentation Systems (VAS) in order to understand the potential for neck pain and injury created by existing systems, and provide insight on the mass and CG properties needed for future systems. NVG use light intensifier tubes to amplify existing light while VAS incorporate both light intensifiers and infra-red thermal imagers. (For the purposes of this report, NVG systems are a sub-set of VAS.) This project had three tasks:

1. Develop a method to measure the mass and CG of VAS.
2. Measure the mass and CG of seven (7) VAS and their associated mounts: AN/PVS-7D, AN/PVS-14, AN/PVS-15A, AN/PVS-23, Fusion Goggles, AN/PEQ-20, Advanced Digital Multispectral (ADM)-NVG. Calculate the neck torque generated by these systems.
3. Develop computational models of the VAS, mounts and helmets with appropriate mass properties to allow virtual measurement of mass, CG and neck torque. Additionally, a virtual model was built of the FGS-PI system.

Each VAS and mount was tested on three (3) sizes of Advanced Combat Helmets (ACHs): Medium, Large and Extra-Large. Additionally, the AMD-NVG was tested on the SOCOM Lightweight Helmet. Each helmet system combination was tested in 4 positions:

- Lowered – Maximum distance
- Lowered – Minimum distance
- Stowed – Maximum distance
- Stowed – Minimum distance

Using the mass and CG measurements collected for the VAS, the neck torques about the atlanto-occipital joint of the neck were calculated. The atlanto-occipital joint is located at the top of the neck where the skull rests. The neck torques for the different systems and configurations ranged from 0.44 N-m to 1.51 N-m (which excluded the effects of the helmet). The helmet imposes a negative torque on the neck ranging from -0.43 N-m (medium ACH) to -0.52 N-m (extra-large ACH). This negative torque of the helmet reduces the neck torque effects of the VAS and mount. When the US Army Aeromedical Research Laboratory's (USAARL's) neck torque criteria for rotary-wing aviators is applied to the data collected, there were only 3 test conditions which exceeded their criteria[2]. These were with the AN/PVS-15 and Wilcox mounts in the stowed position on the large and extra-large ACHs.

In addition to measuring the mass and CG of the VAS, mounts and helmets, the project also created computational models of the components (VAS, mounts and helmets) which incorporated their mass properties. This was done so that the effects on neck torque of changing the helmet, VAS or any of its components could be estimated without conducting experimental testing.

2. Introduction

VAS provide soldiers with the opportunity to “own the night” by allowing them to conduct missions under the cover of darkness. The addition of infrared thermal imaging to traditional light amplification of NVGs is transforming them into VAS. Although the performance of VAS has improved over the years, these systems add significant head-borne mass to the Warfighter's helmet.

VAS increase the weight of the helmet and shifts the CG from its normal position, thus increasing the torque imposed on the neck. Neck torque is a well documented source of neck fatigue and injuries, particularly in high-speed fighter aircraft[3,4]. In ground operations, neck torque can be exacerbated by shock and vibration from activities such as riding in ground vehicles, running or any activity that has impulse forces[5]. Also, as the CG of the helmet is shifted by these systems, it increases the tendency for the helmet to rotate on the head.

This study had 3 tasks:

1. Develop a test method to characterize the mass and CG for VAS
2. Measure the mass and CG of VAS. Calculate the neck torque from the measurements.
3. Develop computational models that include mass properties so that modeling can be used to examine alternatives that could not be tested.

Table 1 lists the systems that were investigated in this study:

Table 1 – List of VAS, helmet mounts and helmets investigated in this study.

VAS	Mount	Helmets
AN/PVS-7D	Norotos, Standard Issue	M, L and XL ACH
AN/PVS-14	Norotos, Standard Issue	M, L and XL ACH
AN/PVS-15	Norotos Low Profile, (USASOC) Wilcox Low Profile, (WARCOM)	M, L and XL ACH
AN/PVS-23	ITT F5050 (USASOC)	M, L and XL ACH
Fusion Goggles	ITT F5050 (USASOC)	M, L and XL ACH and SOCOM LWH – Large
AN/PEQ-20	AN/PEQ-20 ENVG Mount	M, L and XL ACH
ADM-NVG	ADM Wilcox Mount	M, L and XL ACH and SOCOM Lightweight Helmet (LWH) - Large
FGS-PI	ITT F5050 (USASOC)	M, L and XL ACH and SOCOM LWH - Large

- Computational/Virtual Model Only

3. Review of Previous Work

While the helmet greatly outweighs the VAS studied, the CG of the helmet is slightly behind that of the human head, resulting in a slight backward pull during activity. In contrast, VAS exerts a forward torque that moves the CG of the helmet/VAS forward and higher than the CG of the human head. Warfighters can sustain acute or chronic neck injuries if these head-borne masses exceed injury thresholds. These injury thresholds are driven by a combination of 4 factors: weight, CG, exposure time and shock/vibration which can amplify the weight and change the direction of force.

There are 5 types of neck loading that are of concern for potential injury: bending, compression, tension, torque, and shear[1]. Each of these has associated acute and chronic injury thresholds that vary with many factors. While there is a significant amount of scientific literature on the effect of helmets on the health of the human neck, little of it has relevance to dismounted combat operations. Much of the literature focuses on acute neck injury, particularly from ejection seats[6, 7], High G maneuvers[3,4], or in a crash environment[8, 9]. From these studies, a region of acceptable CG locations as a function of helmet mass has been defined called a “Knox” box. The Air Force Research Laboratory (AFRL) has recently conducted neck fatigue testing of seated subjects wearing helmets with different masses and CGs[10]. Some of the most relevant research to this study was conducted by USAARL on the effects of helmet weight on rotary-wing aviators using seated subjects in a whole-body vibration environment [2, 11, 12, 13]. USAARL has also surveyed the use of counterweights by rotary-wing pilots to reduce neck fatigue [14].

The shock and vibration environment found in rotary-wing operations is different from dismounted operations. The shock and vibration environment of rotary-wing aircraft is predictable and well understood. The pilot is in a fixed, seated position and turns his/her head to maintain situational awareness and acquire targets. While this environment is relevant to SOCOM’s rotary-wing units, the environment for mounted and dismounted operations is significantly different. Dismounted operations are characterized by activities such as marching, close-quarter battle, sprinting to cover, climbing obstacles and diving to the ground. SOCOM also has high-speed platforms, such as fast boats and fast attack vehicles that may expose soldiers to extremely large shock and vibration forces.

Dismounted Operations - There is limited work that has been conducted specifically for dismounted operations. In USARIEM Technical Report T07-09, researchers characterized the mass properties of the PASGT and ACH helmets with and without AN/PVS-14 for a dismounted soldier; however, a helmet torque limit was not established.[5] This study also measured the peak accelerations during a variety of dismounted combat activities.

Existing Standards - The work to establish helmet torque standards based on neck fatigue has been conducted by USAARL. In a series of publications on seated, rotary-wing aviators exposed to whole body vibration, USAARL has recommended a limit of 82.8+/- 22.8 N-cm about the occipital condyles[13] or a max of 105.6 N-cm[2].

Counterweights – Shifting the CG of the helmet is one solution to reduce neck fatigue. Shifting the CG of the VAS-equipped helmet closer to that of the head has several benefits. By improving the balance, not only is the static effort to hold the head level reduced, but the tendency for the helmet to rotate while running (or other head acceleration maneuvers) decreases, reducing the effort needed to stabilize the helmet while running.

This shift can be accomplished two ways: 1) Shifting the batteries (and other components that can be shifted) to the back of the helmet. 2) Adding additional weight to the back of the helmet. Adding weight to the back of the helmet increases the inertia, potentially increasing the effort to turn or aim the helmet in a particular direction.

The research on the benefit of adding additional weight to counterbalance VAS is not conclusive. Some testing has shown a benefit to adding additional weight to the back of the helmet to counterweight the VAS [14], while others show little benefit[15]. In the study on ANVIS, a sample of 56 rotary-wing students and instructors was surveyed on the use of helmet counterweights. In this survey sample, the use of counterweights was optional based on personal choice. 76% of those surveyed used added counterweight to offset the weight of the VAS, with an average counterweight of 11.7 oz.

In a different study, Knight and Baber used 20 seated subjects who aimed their helmet at one of five targets located in front of them at various angles[15]. The subject's perception of pain and discomfort was recorded before, during and after each test using the Borg CR-10 scale. In the normal condition they added the weight to the front of the helmet; in the counterbalanced condition they added additional weight to offset the effect of the weight added to the front. This testing showed that the addition of counterweight on average increased, not decreased, the perception of pain (Figure 1). However, this effect was not statistically significant.

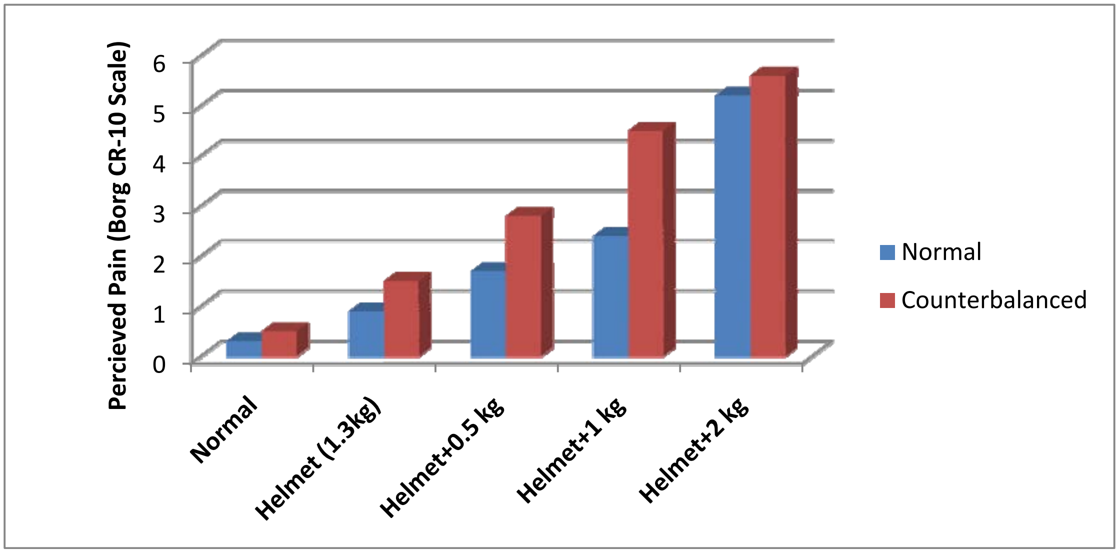


Figure 1 – Effect of helmet weight and counterweight on perceived pain.[15]

Phillips and Petrofsky[16] results showed that for helmets weighing 4 kg, shifting the weight rearward towards the CG as much as possible improves muscle endurance. However, the results also suggest that the addition of weight purely to shift the CG may not improve endurance sufficiently to offset the negative effects of the additional weight.

It may be that the environmental conditions (running, static seated, whole-body vibration etc) and task (aiming vs. scanning for situational awareness) determine if the benefits of adding additional weight to move the CG of the helmet out-weighs the inertial effects of the additional mass.

4. Test Procedure Development

This project developed a test procedure and dedicated fixture for measuring the mass and CG of VAS components. The CG test frame measures the reaction forces of a platform on which the components of interest are mounted. As seen in Figure 2, the fixture uses a standard, commercially-available headform which is mounted in an aluminum frame. This frame is supported in three (3) locations with short stand-offs that rest on scales. The drawing for the fixture is shown in Figure 3.

Key in the design of the frame was its stiffness because frame flexure would produce CG errors when it was switched between orientation #1 and #2. To minimize this flexure, 3/4” angle aluminum alloy was chosen and all joints, except for the headform, were welded. Finite element modeling was conducted to optimize the standoffs so as to minimize deflection without introducing excessive weight (Figure 4).

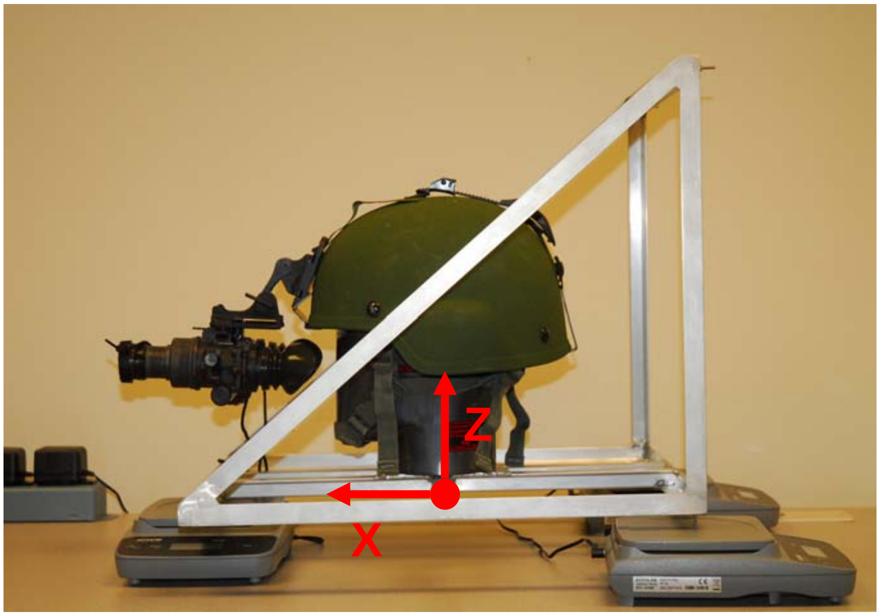


Figure 2 – Fixture for measuring mass and CG properties of VAS components.

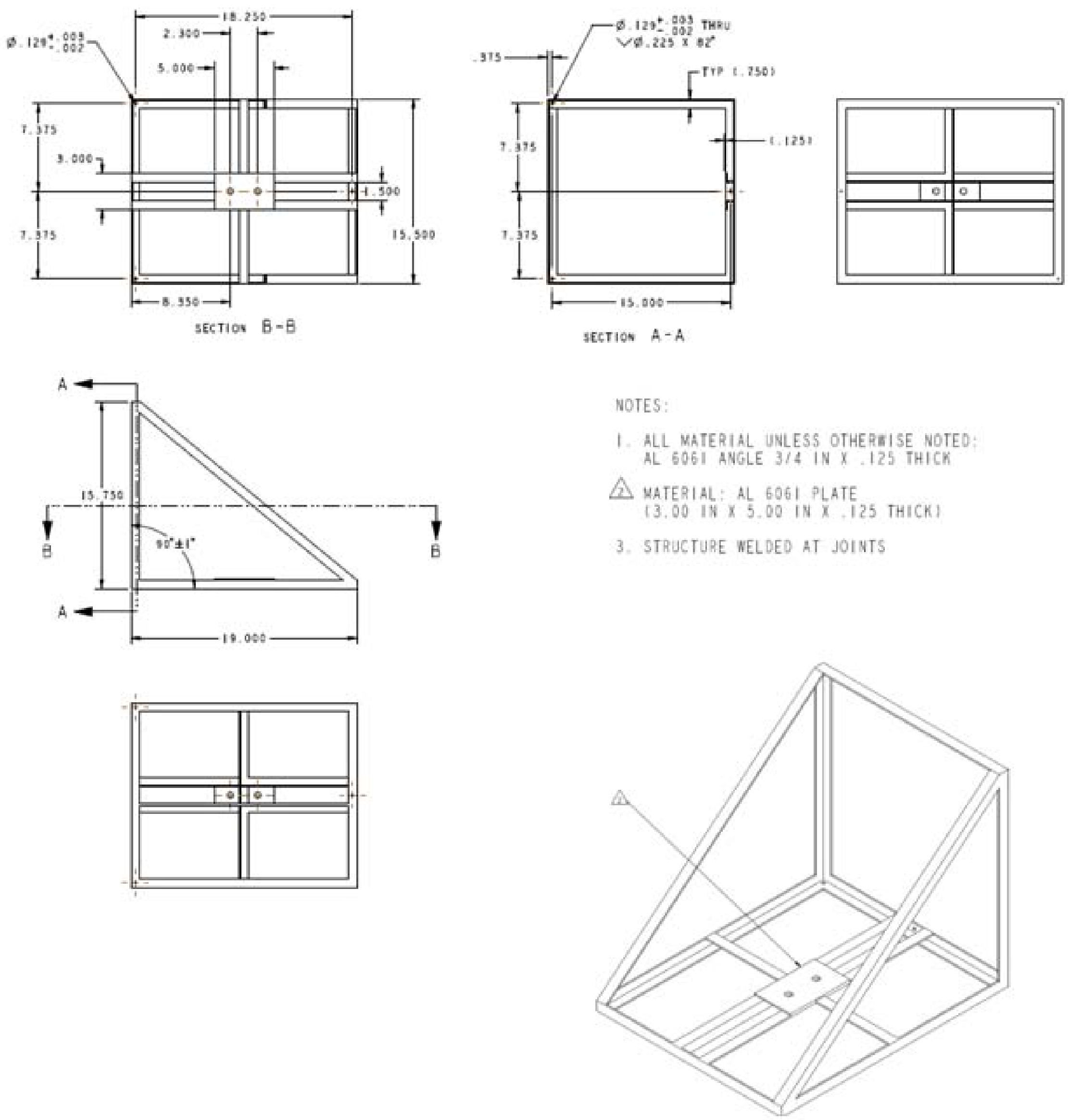


Figure 3 – Drawing of the fixture to measure helmet mass.

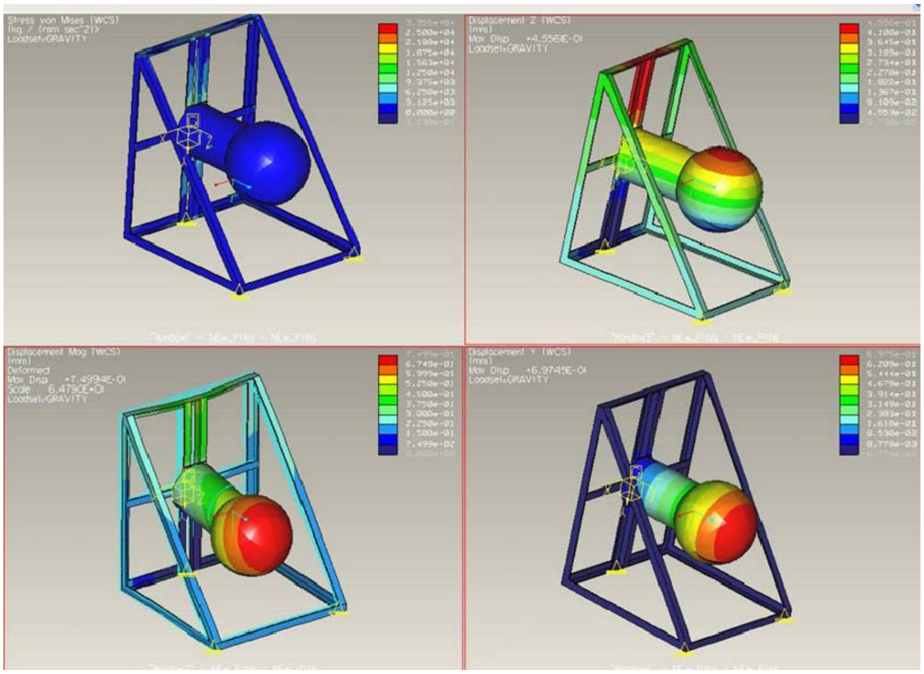


Figure 4 – Results of finite element model showing frame deflection in orientation #2.

Using the measurements of the three scales and the distance between the stand-offs, the total mass and center of gravity can be determined. To determine the CG, measurements are taken in two orientations, Orientation #1 and #2 (Figure 5). Each measurement provides the coordinates of the balance point for the plane of the scale. Since the two orientations are orthogonal to each other, the intersection of lines drawn perpendicular to planes at the balance points provides the coordinates of the CG.

Appendix A discusses the measurement process in more detail.

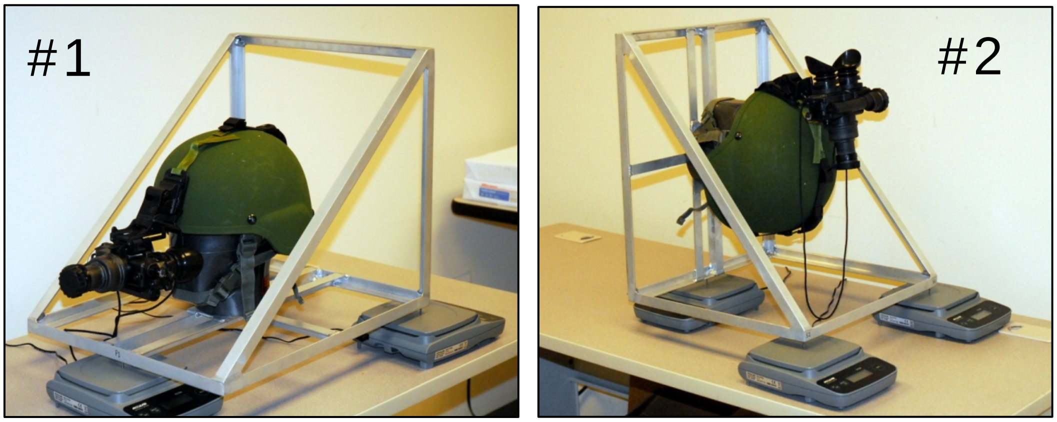


Figure 5 – Example application of the CG Device for measuring the CG locations of helmets and helmet-mounted equipment using two orthogonal orientations.

4.1. Calculation of the Mass and CG

While the total mass is simple to calculate, the CG calculation is more involved. The VAS and helmet mass is the sum of the scale weights once the scales have been zeroed (tared) to remove the weight of the frame and headform.

To calculate the CG of the system, an EXCEL spreadsheet routine was developed that uses the weights measured and the known distances between the stand-offs. This EXCEL spreadsheet, shown in Figure 6, allows the user to enter the weights measured and calculates the mass and CG about the frame's coordinate system. By calculating the CG in the primary and secondary orientation, the CG in all three axes may be determined.

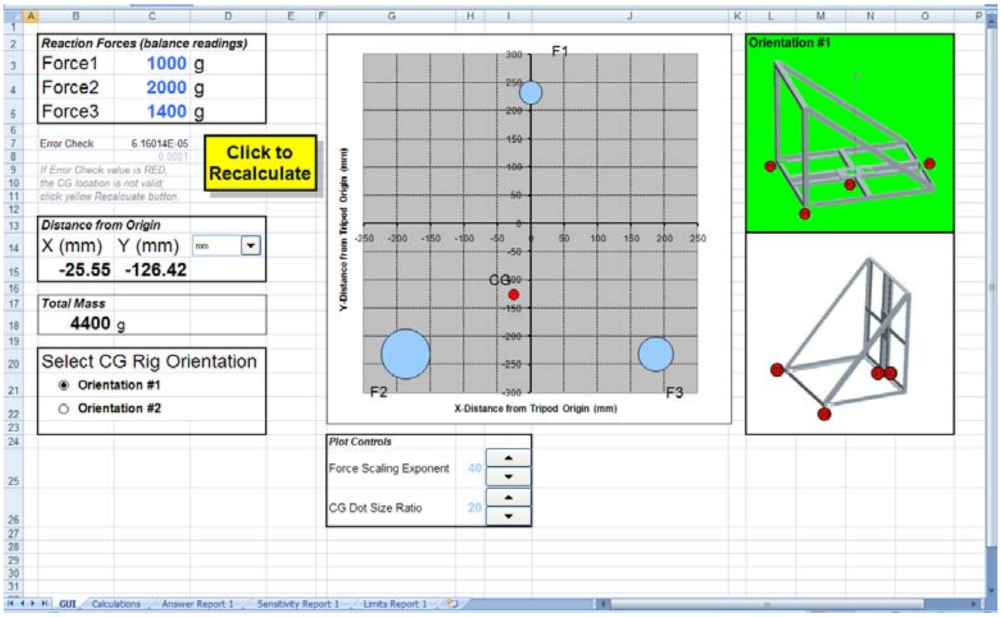


Figure 6 – Screen shot of program that calculates CG.

Measurement Process - The measurement process starts with checking the performance of the scales using known weights. Then the frame and appropriate headform are mounted on scales, with the standoffs located on the center of the scale, and the weight of the frame and headform are zeroed (tared). The frame is removed from the scales and the helmet and VAS of interest are mounted on the headform with the brim of the helmet parallel with the reference line. To standardize the distance between the top of the helmet and the headform, a ½" spacer replaced the crown pad. This ½" spacer resulted in a helmet position that was 9 mm lower than the crown pad.

Two sizes of British Standard (BS) EN 960 headforms were used in the testing: Cadex Size J, (570 mm Circumference) and Cadex Size M (600 mm Circumference). Size J was used for the medium and large helmets, while Size M was used for the X-Large helmet. The VAS were tested in 4 arrangements, down and in the stowed positions with the VAS located at two positions on their track, at the maximum and minimum locations. This produced 4 CG measurements per helmet/VAS combination:

- Lowered – Maximum
- Lowered – Minimum
- Stowed – Maximum
- Stowed – Minimum

In the down position, the VAS is mounted so that the eyepiece was located slightly above the basic plane of the headform; the basic plane is located along the Frankfort plane of the human head at the bottom of the eye. The VAS is mounted in the down position so that their visual axes are parallel with the ground. The maximum distance is the furthest location that the VAS can be mounted on the track away from the headform, while the minimum distance measured places the eye piece as close as possible to the headform. Additionally, measurements were made of the VAS in the stowed position over the helmet in both the minimum and maximum positions. The chin strap was tightly fastened to prevent shifting of the helmet between Orientation #1 and #2. The standard VAS mounting brackets were employed except in cases where it required modification of the helmets. In these cases, stiff, fibrous tape was used to affix the VAS (and battery pack where needed) in the proper location. Tape was used for the AN/PVS-23, Fusion, and ADM-NVG on the SOCOM Helmet. Care was taken to assure that the VAS did not shift when the helmet was tipped between Orientation #1 and #2.

After the 4 measurements were taken, the helmet and VAS were removed and reinstalled on the headform and repeated measurements were taken to determine the repeatability of the installation and weighing process. This was done until each measurement has been made a total of three times. With three (3) weight measurements per orientation, two (2) orientations per CG measurement, and four CG measurements per helmet/VAS combination, 24 weight measurements were made per helmet/VAS combination.

4.2. Test Fixture Validation

The CG test frame measurements were validated by placing a uniform cylindrical test mass at specific locations on the platform that were measured independently with calipers (Fowler, +/- 0.001”). By comparing the measured location with the calculated location of the mass, the accuracy of the CG measuring system could be assessed. The testing showed that the difference between the CG device measurement and the known locations of the test mass was very small - sufficiently small to attribute the difference to the ability to measure the test mass location, not to the calculation (Figure 7).

The green circles in Figure 7 represent the locations of test masses in relation to the reaction force locations (blue circles). The histogram included in Figure 7 shows the difference between the CG device measurements and the caliper measurements. While the accuracy possible with the CG device is expected to be better than what is reflected in the histogram, the ability to accurately measure the position of the test mass was likely the main source of errors observed. The validation measurements show that sufficient accuracy is achieved for this application’s purpose. In addition to the locations shown in Figure 7, the calculation space has been validated for the entire area inside and outside of the reaction force triangle.

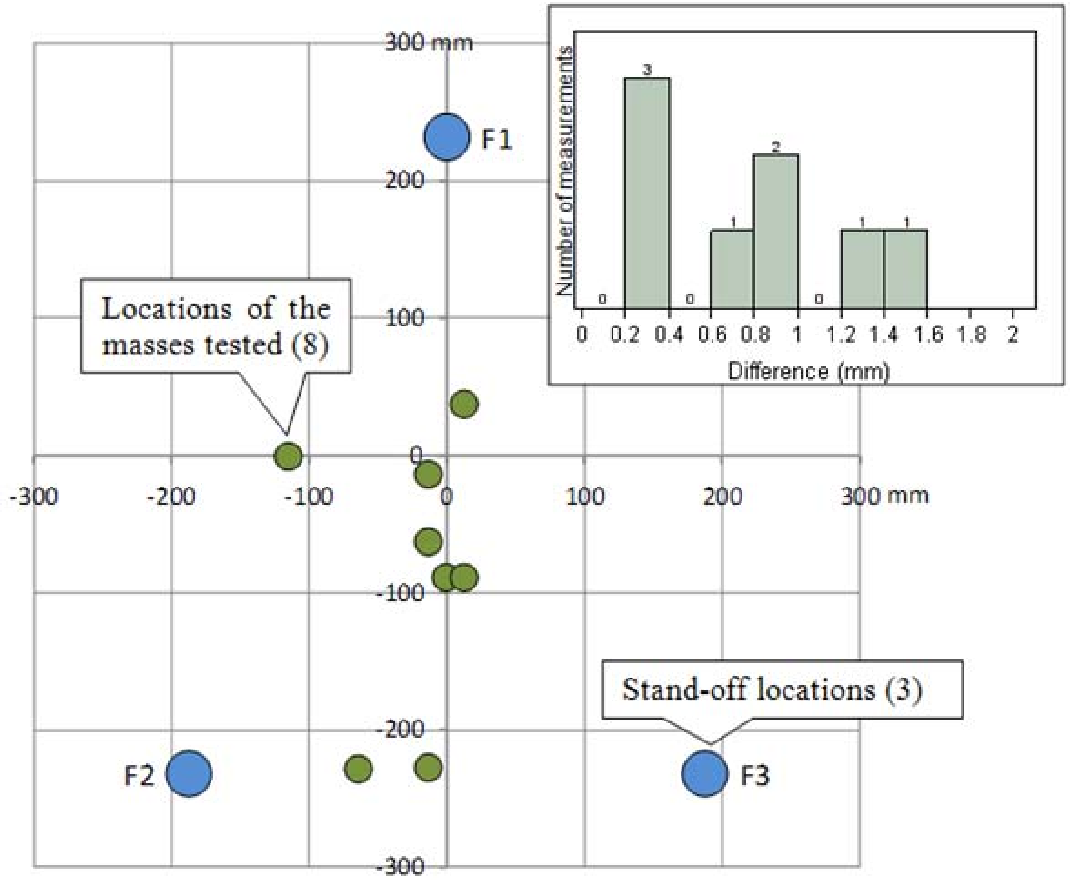


Figure 7 – Validation test cases for the CG device. The inset histogram shows the distribution of the differences between the CG device measurements and the ruler measurements

4.3. Mapping of Results to Human Anatomical Landmarks

To compare the neck torque limits developed by USAARL[14] to the data collected, the frames of reference need to be the same. Neck torque is the force acting on a moment arm about the axis of rotation. This neck force can be calculated as the product of the CG's mass and acceleration vector, the acceleration being caused by gravity (or other acceleration field). The moment arm is the distance perpendicular to the force vector between the CG and the axis of rotation. In this work, the CG was established by mapping the locations of the 3 frame standoffs in both positions to the base and vertical-transverse and vertical-longitudinal planes of the headform. In the USAARL work, the atlanto-occipital (AO) complex was used as the axis of head rotation. USAARL determined the axis or rotation one of two ways: either from measuring the rotation of the head using a bit fixture during movement, or from radiographs where they determined that the atlanto-occipital complex averaged approximately 20.5 mm rearward and 29.8 mm down from external auditory meatus for the subjects they measured[13]. (The tragion, which is at the top of the tragus, is the part of the outer ear just in front of the external auditory meatus (see Figure 8) and lies about 2.5 mm above and in front of the porion[17].)

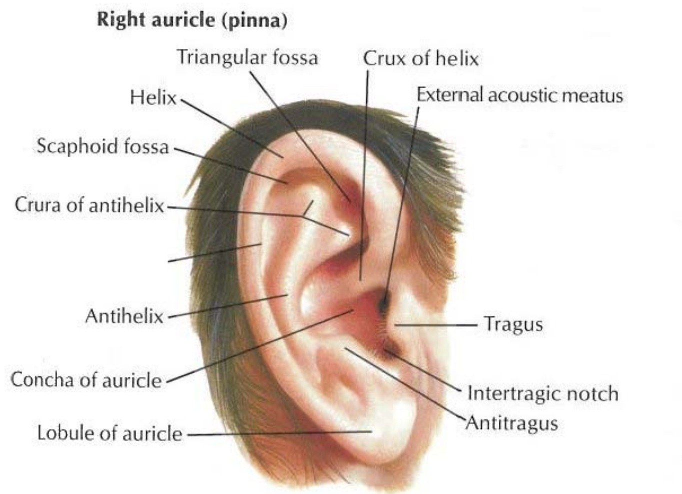


Figure 8 – Coronal view of ear anatomy[18].

The next parameter to be determined is the horizontal distance between the atlanto-occipital complex from the vertical-transverse plane of the headform. The vertical-transverse plane on the EN-960 headform is located mid-way between the front and rear extremities of the headform (See Figure 9 and Table 2).

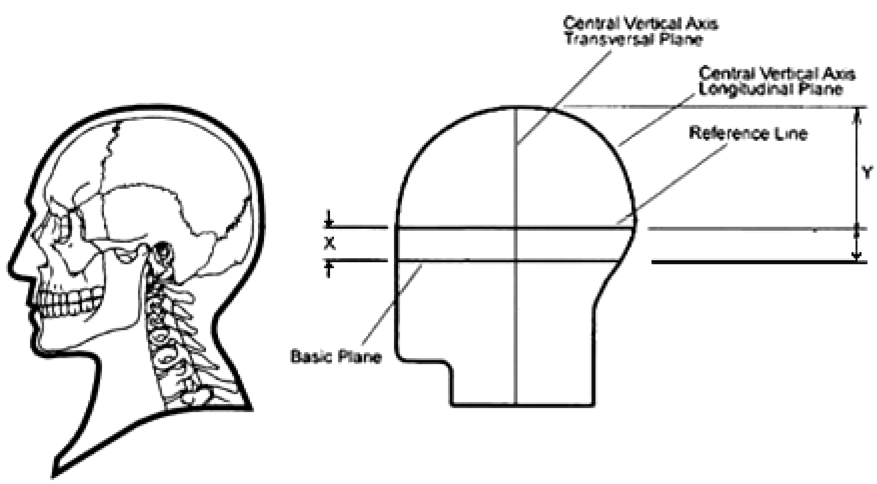


Figure 9 – Comparison of human head and EN-960 Headform. [19]

Table 2 – Comparison of human landmarks to those found on the EN-960 headform.

Human Landmark	EN960 Landmark
Top of head	Intersection of vertical longitudinal and transverse planes
Glabellas	Intersection of Reference and vertical longitudinal planes, Front
Back of head	Intersection of Reference and vertical-longitudinal planes, Back
Frankfort plane	Basic Plane
External auditory meatus	Approximately aligned with Central Vertical Axis and the Basic Plane
Atlanto-occiptial complex	20.5 mm rearward and 29.8 mm down from external auditory meatus.[13]

The vertical alignment of the two frames of reference can be accomplished by aligning the basic plan of the headform with the Frankfort plane of the human head. In the EN960 headform, the basic plane corresponds to the Frankfort plane which passes through the orbitale, the lowest point on the rim of the bony orbit, to the porion, the most lateral point in the middle of the bony roof of the external auditory meatus.

The horizontal distance between the two frames of reference is most important because it is part of the neck torque calculation. The horizontal distance was determined using several dimensions (Figure 10):

1. Head Length (Dimension 63 in the 1988 Anthropometry Survey[20], the distance from the glabellas landmark to the back of the head). Half of this value is the distance of the mid-line to the back of the head. The midline is the location of the coronal plane of the head.
2. Distance between the tragion - back of the head dimension (Dimension H43). Subtracting 20.5mm (the distance between the AO complex and tragion) results in the distance between the back of the head and the AO complex.
3. Subtracting the distance from the back of the head to the AO from the distance to the midline results in the distance between the AO complex and the midline.

As shown in Figure 11 the horizontal distance varies with the size of the head from 24.9mm to 16.8mm.

Comparing the CADEX headforms to the 50th percentile male shows that the Size J headform is 2.5 mm larger in circumference, corresponding most closely to a 55th percentile male (569.4 mm circumference). Comparing the Size M headform to the 95th percentile male shows the circumference of the headform is 6.5 mm larger, corresponding most closely to a 98th percentile male head (601mm circumference).

Since these values are averages of measurements that range significantly with human variability, for the purposes of this analysis, the AO complex is approximately 32.3 mm below and 21.2 mm behind the intersection of the basic plane and the midline plane of the EN-960 J headform for the medium and large helmets. For the extra large helmet and M headform, the AO complex is approximately 32.3 mm below and 16.8mm behind the midline plane.

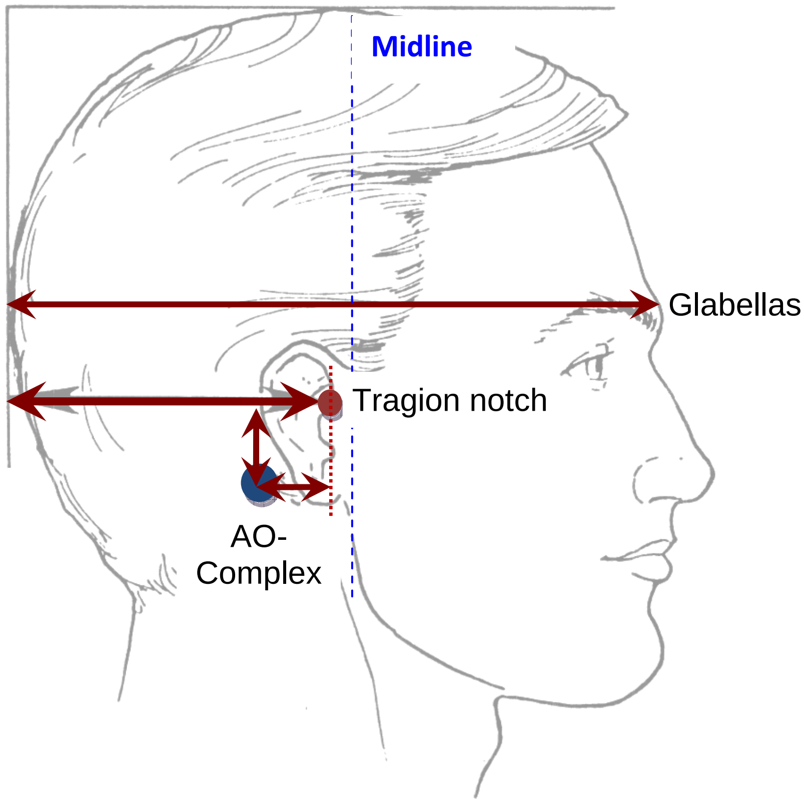


Figure 10 – Illustration of head dimension calculations.

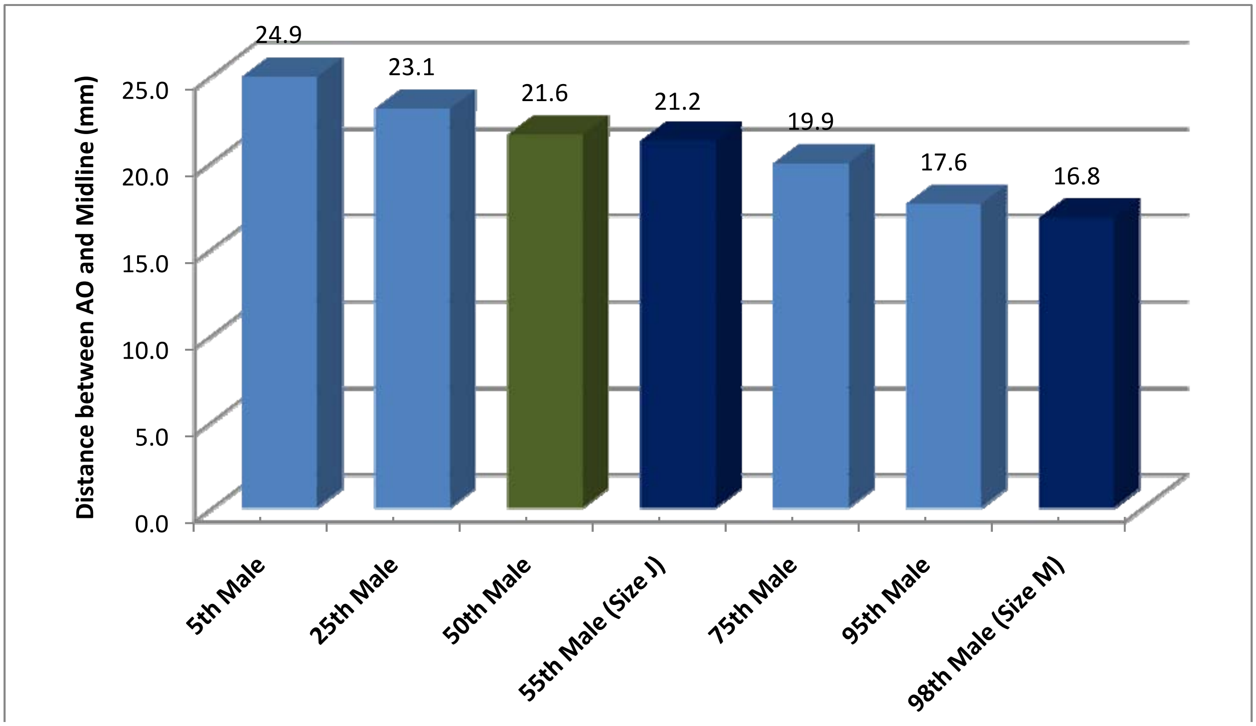


Figure 11 – Distance between AO complex and the midline plane of male heads and the J and M CADEX headforms.

5. Mass, CG and Neck Torque Measurements

Using the offsets described in Section 4.3, the neck torque for the data collected can be calculated. Table 3 lists the neck torque about the AO-complex for the seven (7) VAS evaluated. (AN/PVS-15 was evaluated with two mounts.) Each system was measured with three ACH helmets: Medium, Large, and Extra Large. The SOCOM lightweight helmet (Large) became available at the end of the evaluation period and was tested with one VAS - the ADM-NVG. Table 4 lists the mass, CG, and neck torque about the AO-complex induced by the VAS and mount, excluding the torque of the large ACH.

Figure 12 plots the data from Table 3 and compares the neck torque from different VAS in the four positions. It shows that the AN/PVS-15, particularly with the Wilcox mount, produces some of the highest neck torques measured. As expected, the Lowered-Maximum position produced more neck torque than the Lowered-Minimum position. Not quite as obvious was that the Stowed-Minimum position usually produced more neck torque than the Stowed-Maximum because the stowed track tilted backwards.

For the AN/PEQ-20, the minimum stowed position was not at the minimum position on the track because the helmet interfered with the VAS in this location. Instead, the AN/PEQ-20 was placed in the lowest position possible in the stowed position.

While for many of the VAS the stowed position reduced neck torque, for others, it increased. For this VAS, the stowed position was more up and forward of the helmet, rather than up and back.

Of the data collected, only 3 positions of the AN/PVS-15 (with the Wilcox mount) on the large and extra-large ACH exceeded the neck torques limits (1.056 N-m) established by USAARL for rotary-wing aviators[2].

Table 3 – Measurements of neck torque for different helmets and VAS components about the AO-complex.

			Helmet and VAS (N-m about AO)			
Component	Position	Extension	ACH, Medium	ACH, Large	ACH, X-Large	SOCOM Lightweight
Helmet Alone			-0.43	-0.44	-0.52	-0.51
AN/PVS-7						
	Lowered	Max	0.79	0.87	0.84	nm
	Lowered	Min	0.54	0.62	0.58	nm
	Stowed	Max	0.05	0.13	0.02	nm
	Stowed	Min	0.31	0.38	0.30	nm
AN/PVS-14						
	Lowered	Max	0.51	0.57	0.54	nm
	Lowered	Min	0.37	0.39	0.35	nm
	Stowed	Max	0.08	0.14	0.06	nm
	Stowed	Min	0.31	0.35	0.25	nm
AN/PVS-15 (Norotos)						
	Lowered	Max	0.91	0.98	0.90	nm
	Lowered	Min	0.68	0.72	0.68	nm
	Stowed	Max	0.53	0.62	0.56	nm
	Stowed	Min	0.79	0.88	0.80	nm
AN/PVS-15 (Wilcox)						
	Lowered	Max	0.96	1.03	1.04	nm
	Lowered	Min	0.79	0.86	0.86	nm
	Stowed	Max	0.96	1.06 [A]	1.00	nm
	Stowed	Min	1.05	1.14 [A]	1.11 [A]	nm
Fusion Goggle						
	Lowered	Max	0.59	0.58	0.57	0.54 [B]
	Lowered	Min	0.46	0.37	0.39	0.33 [B]
	Stowed	Max	0.52	0.47	0.50	0.57 [B]
	Stowed	Min	0.68	0.63	0.66	0.69 [B]
AN/PVS-23						
	Lowered	Max	0.35	0.35	0.34	nm
	Lowered	Min	0.29	0.25	0.24	nm
	Stowed	Max	0.40	0.36	0.34	nm
	Stowed	Min	0.48	0.43	0.43	nm
AN/PEQ-20						
	Lowered	Max	0.51	0.47	0.50	nm
	Lowered	Min	0.35	0.29	0.38	nm
	Stowed	Max	0.09	0.09	0.09	nm
	Stowed	Min	0.19	0.15	0.18	nm
ADM-NVG						
	Lowered	Max	0.14	0.16	0.16	0.09
	Lowered	Min	0.05	0.02	0.04	-0.04
	Stowed	Max	0.20	0.20	0.16	-0.10
	Stowed	Min	0.26	0.25	0.22	-0.01
FGS-PI						
	Lowered	Max	0.41 [B]	0.43 [B]	0.48 [B]	0.43 [B]
	Lowered	Min	0.25 [B]	0.27 [B]	0.33 [B]	0.28 [B]
	Stowed	Max	0.44 [B]	0.46 [B]	0.51 [B]	0.46 [B]
	Stowed	Min	0.49 [B]	0.51 [B]	0.51 [B]	0.52 [B]

nm – Not measured.
– [A] Values exceeding USAARL standards.
– [B] Values determined using computational/virtual modeling.

Table 4 – Measured mass and CG of VAS and mounts excluding helmet effects. Neck torque of the VAS and mounts are calculated without the helmet.

			VAS and Mount on Large ACH (ACH weight excluded)				
				CG Location from AO (mm)			Neck Torque (N-m about AO)
Component	Position	Extension	Mass (g)	x	y	z	
AN/PVS-7 (Norotos)							
	Lowered	Max	777	171.5	0.6	-32.9	1.31
	Lowered	Min	776	138.4	0.0	-33.7	1.05
	Stowed	Max	777	73.1	-0.7	126.4	0.56
	Stowed	Min	777	106.8	-0.5	120.5	0.81
AN/PVS-14 (Norotos)							
	Lowered	Max	671	152.6	27.2	-30.7	1.00
	Lowered	Min	671	124.7	27.8	-30.7	0.82
	Stowed	Max	671	87.0	28.0	120.9	0.57
	Stowed	Min	671	118.7	28.4	115.3	0.78
AN/PVS-15 (Norotos)							
	Lowered	Max	884	162.8	1.9	-27.8	1.41
	Lowered	Min	883	133.0	1.6	-28.6	1.15
	Stowed	Max	884	121.1	2.3	111.9	1.05
	Stowed	Min	884	151.4	2.8	105.3	1.31
AN/PVS-15 (Wilcox)							
	Lowered	Max	904	164.6	2.7	-30.3	1.46
	Lowered	Min	905	145.5	2.4	-31.3	1.29
	Stowed	Max	904	168.5	1.5	63.5	1.49
	Stowed	Min	905	177.5	1.8	47.1	1.57
Fusion Goggle							
	Lowered	Max	1371	75.6	-0.3	-24.1	1.02
	Lowered	Min	1371	60.3	0.6	-21.4	0.81
	Stowed	Max	1371	67.5	-1.1	57.8	0.91
	Stowed	Min	1371	79.4	-0.4	41.1	1.07
AN/PVS-23							
	Lowered	Max	924	87.6	-1.2	-19.2	0.79
	Lowered	Min	924	76.1	-1.1	-18.9	0.69
	Stowed	Max	923	89.2	1.1	57.4	0.81
	Stowed	Min	924	96.5	0.5	43.7	0.87
AN/PEQ-20							
	Lowered	Max	931	96.7	-17.7	-18.1	0.88
	Lowered	Min	931	77.8	-18.7	-17.3	0.71
	Stowed	Max	931	55.6	-39.1	66.3	0.50
	Stowed	Min	931	62.6	-41.4	41.9	0.57
ADM-NVG							
	Lowered	Max	1074	54.5	3.1	-8.0	0.57
	Lowered	Min	1074	41.4	2.8	-7.0	0.44
	Stowed	Max	1074	58.6	-0.5	82.0	0.62
	Stowed	Min	1074	63.4	1.1	69.8	0.67

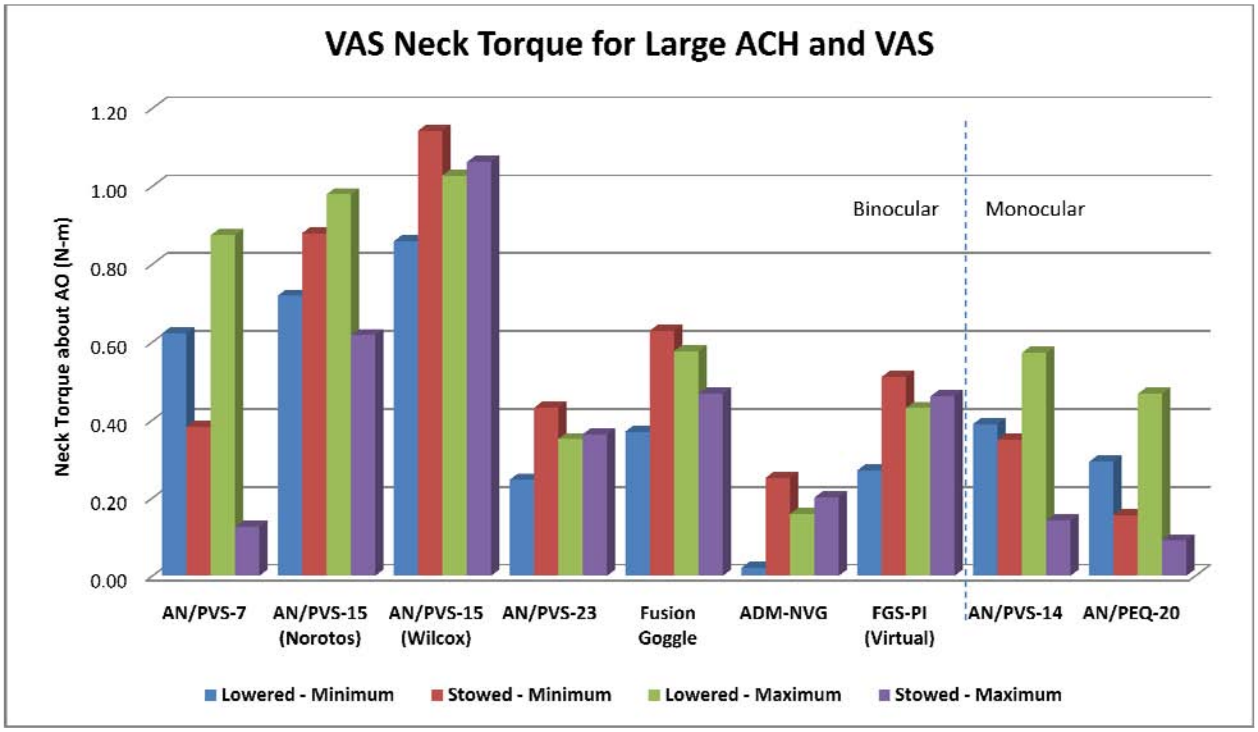


Figure 12 – Plot comparing the neck torque from different VAS and positions on a large ACH.

6. Computer Model Development

Computer models of the components measured were developed using Pro-Engineer. Attachment B contains a CD with the Pro-E Computer Aided Design (CAD) files of VAS and Helmets.

VAS Models - In addition to the system measurements discussed in Section 5, each goggle and mount was measured independently to generate the mass properties and CG location of the individual components. CAD models of each component were generated with sufficient detail to provide the likeness of the object while maintaining the feature details needed for assembly.

The individual components were measured in a similar manner as the helmet-VAS systems, the difference being that the components were placed on a triangular plate instead of the CG test frame. Each component was measured by lining up two reference planes from obvious features of the component with the triangular plate's coordinate system. Two to three orientations or each component were measured. Lightweight foam blocks were employed to help orient and balance the components. The contribution of the foam block to the total weight was removed (tared out) before the measurements were made.

Using caliper measurements of the dimensions, the individual components were modeled retaining the important component features as well as the feature planes used in determining the CG. The CG, as calculated by ProE, of the modeled component was compared with the measured value. Material inside the part was then removed to shift the CAD model's CG to the measured location. Once the CG position of the modeled component was correct, the density of the component was adjusted so that the modeled component mass matched that of the actual component. Table 5 shows the CAD models of components generated in this study.

Table 5 – Final CAD models of components.

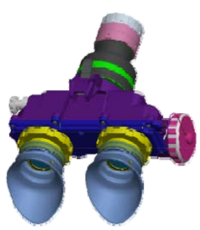
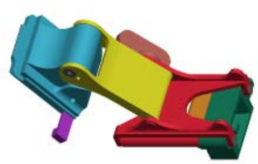
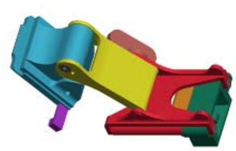
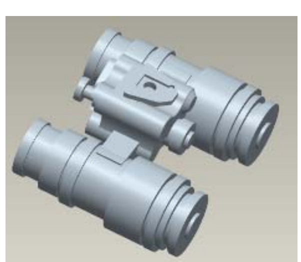
Component	Mount	Battery Pack	Mass (grams)
AN/PVS-7D			
	 Norotos, Standard Issue	None	Goggles: 532 Mount: 153 Battery Pack: None
AN/PVS-14			
	 Norotos, Standard Issue	None	Goggles: 427 Mount: 153 Battery Pack: None
AN/PVS-15A			
	 Norotos Low Profile, (USASOC)	None	Goggles: 647 Mount(Norotos): 239 Battery Pack: None
	 Wilcox Low Profile, (WARCOM)	None	Goggles: 647 Mount(Wilcox): 262 Battery Pack: None

Table 5 (cont.) – Final CAD models of components.

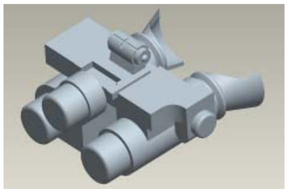
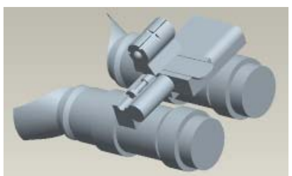
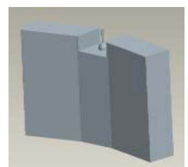
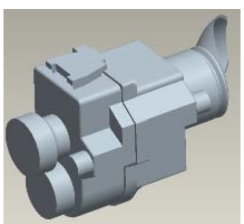
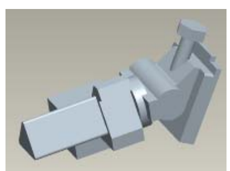
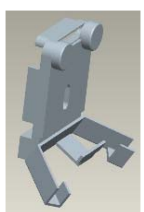
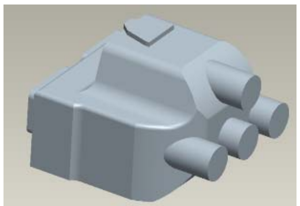
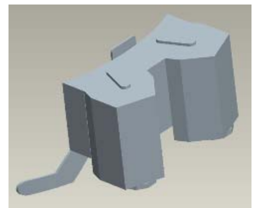
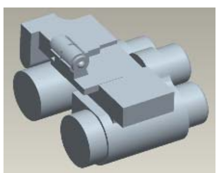
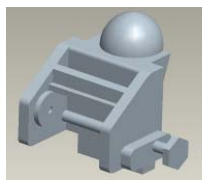
Fusion (FGS-001-A3)			
	 USASOC Mount	 Yes	Goggles: 914 Mount: 78 Battery Pack: 377
AN/PVS-23			
	 USASOC Mount	 Yes	Goggles: 639 Mount: 78 Battery Pack: 196
AN/PEQ-20			
	   AN/PEQ-20 ENVG Mount	 Yes	Goggles: 446 Mount: 230 Battery Pack: 155

Table 5 (cont.) – Final CAD models of components.

Advanced Digital Multispectral - Night Vision Goggle			
	 ADM Wilcox (modified)	 Yes	Goggles: 562 Mount: 147 Battery Pack: 362
FGS-PI ANVS (VIRTUAL)			
	 USASOC Mount	 Yes	Goggles: 645 Mount: 78 Battery Pack: 160
Headset			
			Headset: 475

Helmets and Headforms – CAD models were constructed of the helmets and head forms using geometry generated from 3-D laser scans. The equipment used for the 3-D laser scanning was a Perceptron Contour Probe laser scanning head mounted on a FaroArm position tracking arm. This system creates a point cloud that can be used to reconstruct the surface of a component. A point cloud is an array of three-dimensional coordinates that maps the contours of an object's surface. Geomagic software was used to convert the point cloud into solid object whose surface is defined by Non-Uniform Rational B-Splines (NURBS) (Figure 13).

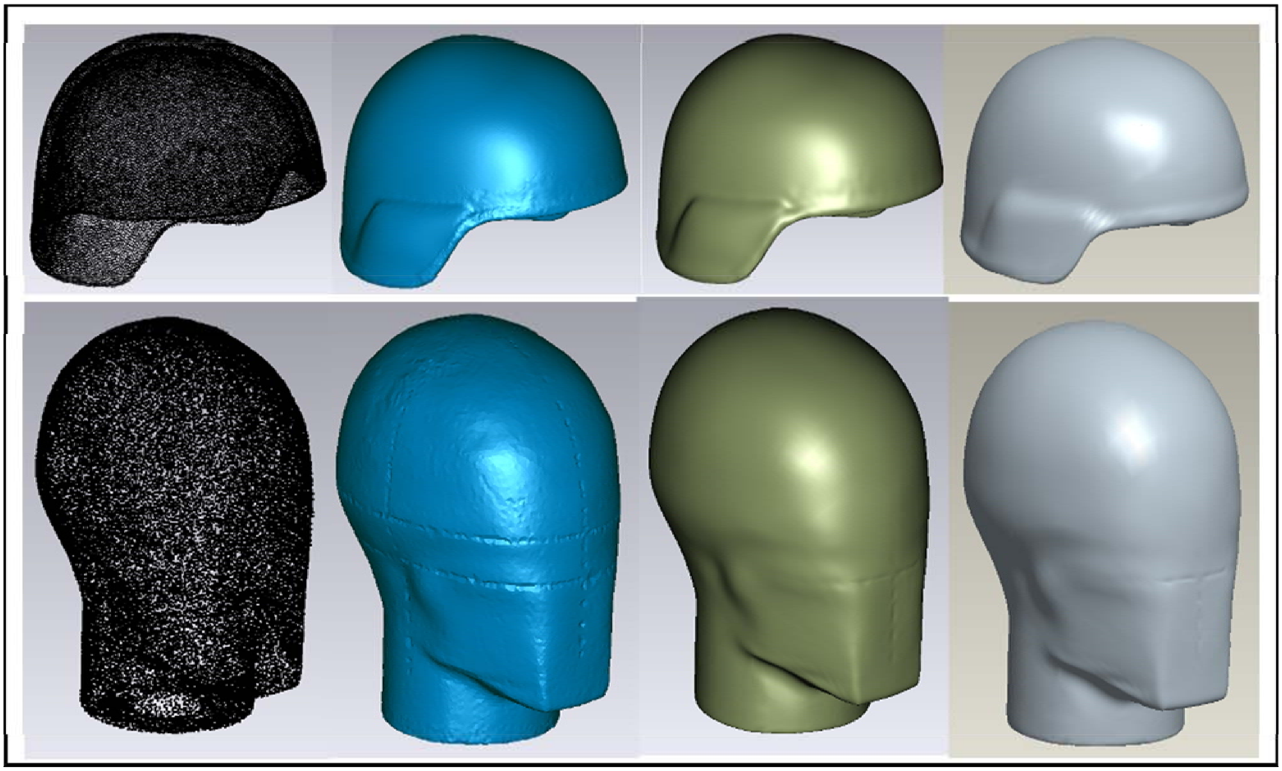


Figure 13 – Images showing the transformation of the initial point cloud (left) through the different stages of modeling to the finished model (right).

Datum planes were generated to identify landmark planes to ease the assembly process. On the headforms, these planes included the reference plane, basic plane, longitudinal plane, and transverse plane. The helmet models include a plane of symmetry (longitudinal plane), horizontal plane, transverse plane and a ½” offset plane. The models were then assembled into the configurations as measured during the system CG measurement using the ½” offset method. A reference coordinate system, the same as used in the test fixture, was applied to the model. The frame, headform and helmet have negligible densities applied to them to minimize their mass effects on the helmet and VAS CG calculation. The CG calculation is recorded for each individual configuration and compared to the experimentally measured results.

Figure 14 shows system assembly models displaying the 4 measured configurations:

- Lowered – Maximum
- Lowered – Minimum
- Stowed – Maximum
- Stowed – Minimum

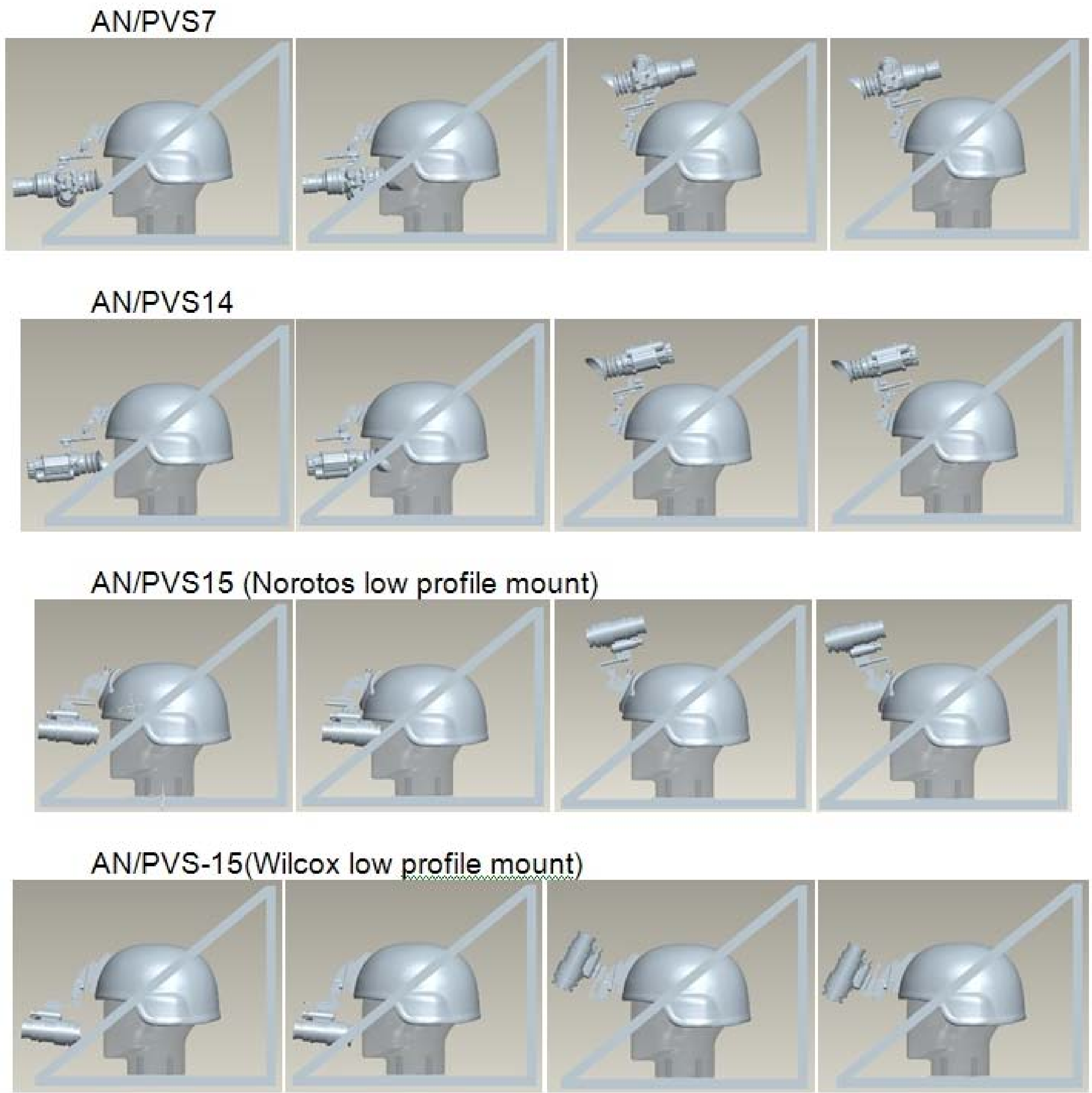


Figure 14 – CAD models of VAS.

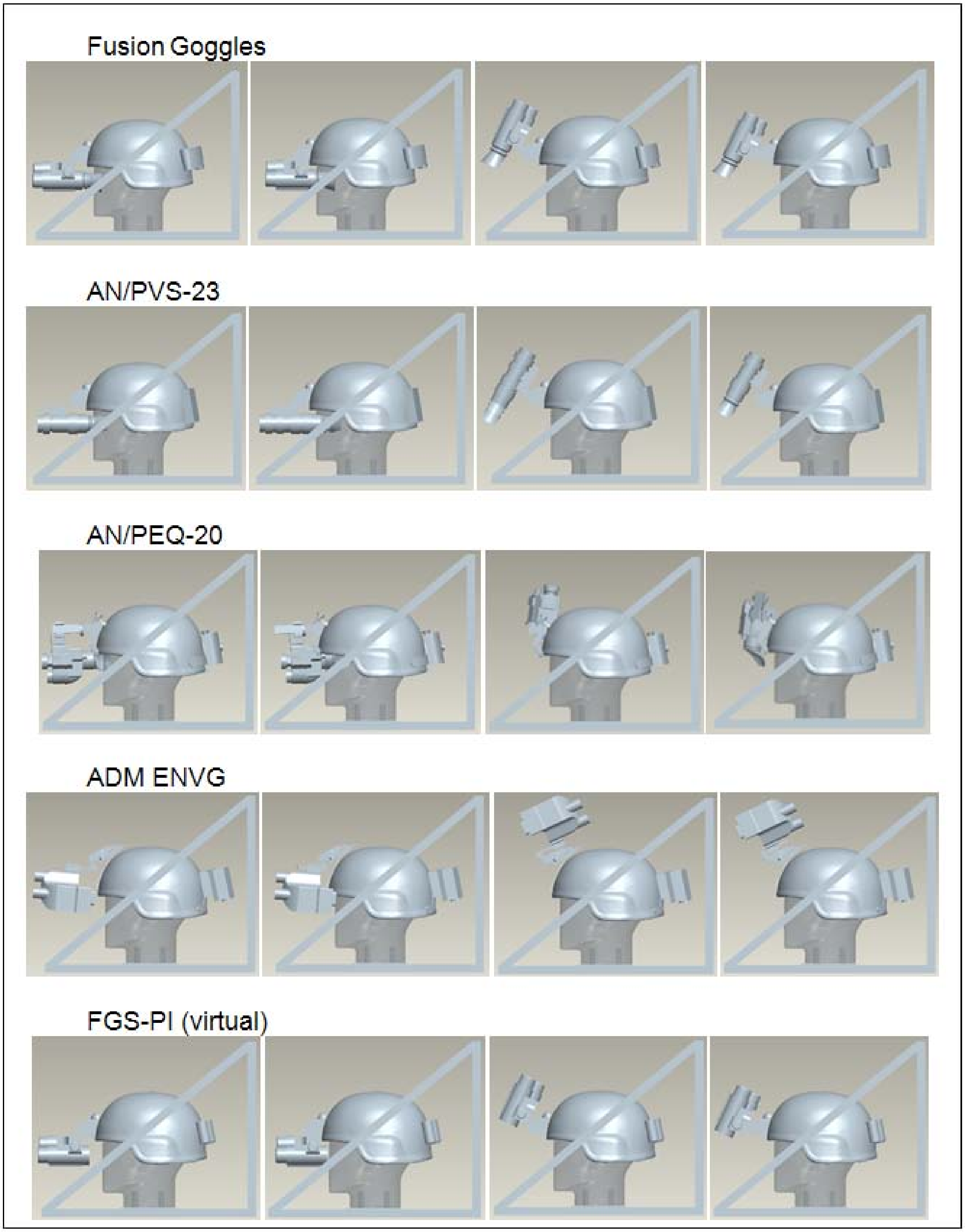


Figure 14 (cont.) – CAD models of VAS.

The results of the computational/virtual models were compared with system measurements that were made.

Table 6 below shows the differences between the computational/virtual models and the system measurements made. The source of the differences between the models and measurements were the result of how the components were assembled in the virtual world. The values calculated were very sensitive to the exact fit of the surface of the mount against the curved helmet.

Table 6 – Difference in neck torque between computational/virtual models and measured value.

			Difference (N-m)			
Component	Position	Extension	ACH, Medium	ACH, Large	ACH, X-Large	SOCOM Lightweight
PVS-7						
	Lowered	Max	0.02	0.11	-0.05	nm
	Lowered	Min	0.03	0.12	-0.04	nm
	Stowed	Max	0.16	0.16	0.08	nm
	Stowed	Min	0.17	0.16	0.09	nm
PVS-14						
	Lowered	Max	0.00	0.07	-0.07	nm
	Lowered	Min	0.07	0.09	-0.05	nm
	Stowed	Max	0.17	0.19	0.1	nm
	Stowed	Min	0.19	0.19	0.08	nm
PVS-15 (Norotos)						
	Lowered	Max	0.08	0.09	-0.07	nm
	Lowered	Min	0.14	0.12	-0.01	nm
	Stowed	Max	0.00	-0.02	-0.17	nm
	Stowed	Min	0.00	-0.02	-0.2	nm
PVS-15 (Wilcox)						
	Lowered	Max	-0.08	-0.04	-0.16	nm
	Lowered	Min	-0.05	-0.01	-0.14	nm
	Stowed	Max	-0.05	0.01	-0.19	nm
	Stowed	Min	-0.05	0.01	-0.16	nm
Fusion Goggle						
	Lowered	Max	0.11	0.08	-0.03	nm
	Lowered	Min	0.20	0.09	0.01	nm
	Stowed	Max	0.01	-0.06	-0.12	nm
	Stowed	Min	0.06	-0.01	-0.08	nm
AN/PVS-23						
	Lowered	Max	0.08	0.08	0.02	nm
	Lowered	Min	0.13	0.09	0.03	nm
	Stowed	Max	0.02	-0.02	-0.09	nm
	Stowed	Min	0.05	-0.01	-0.05	nm
AN/PEQ-20						
	Lowered	Max	0.16	0.09	0.05	nm
	Lowered	Min	0.19	0.11	0.13	nm
	Stowed	Max	0.20	0.16	0.10	nm
	Stowed	Min	0.11	0.04	0.01	nm
ADM-NVG						
	Lowered	Max	0.08	-0.01	-0.07	-0.07
	Lowered	Min	0.13	-0.01	-0.04	-0.07
	Stowed	Max	0.16	0.08	-0.04	-0.13
	Stowed	Min	0.15	0.06	-0.05	-0.12

nm – not measured

When the CGs of the VAS computational models are plotted in Figure 15, the differences in VAS and the 4 positions can be seen. It is clear that the AN/PVS-15 generates greater amounts of neck torque than the other VAS. As seen in Figure 15, the differences in the minimum and maximum track position are small in comparison with the Stowed and Down Positions and the differences in VAS and mounts.

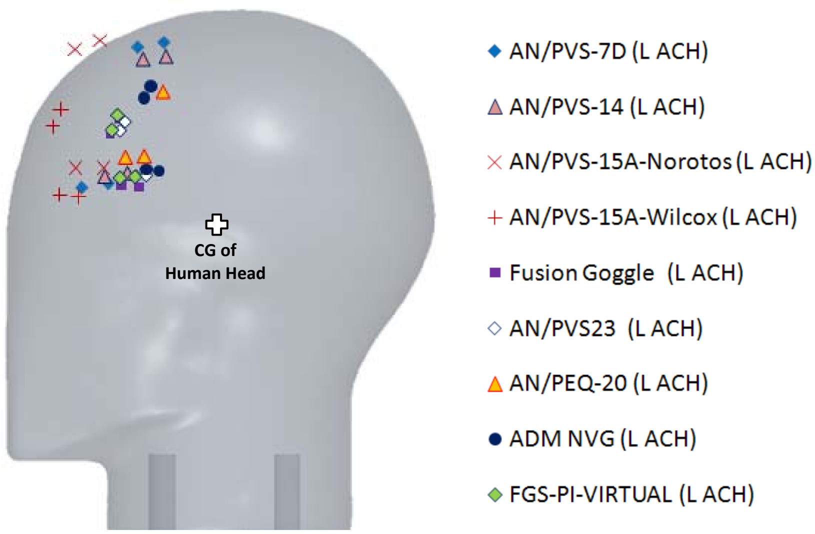


Figure 15 – CG locations plotted over the headform showing how the CG varied with the VAS and position for a large ACH.

Figure 16 compares the Fusion Goggle and ADM-NVG in the 4 positions across the 4 helmets: Medium ACH, Large ACH, X-Large ACH and the SOCOM-LWH (Large). The effect of ACH helmet size is small, on the same order as track position. The large SOCOM LWH helmet produces a slightly smaller neck torque than the large ACH; however, the CG is higher on the head possibly exerting more torque in a frontal vehicle crash.

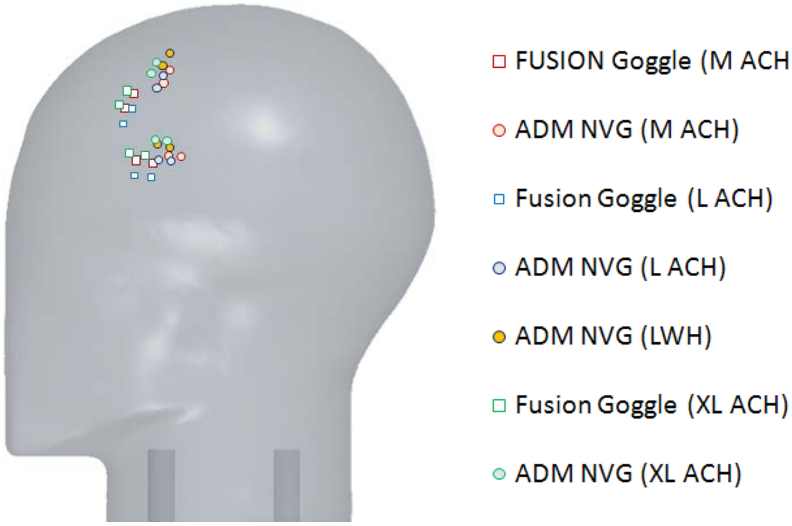


Figure 16 – Comparison of Fusion and ADM NVG systems across the 4 helmets tested.

7. Future Work

This effort highlights two key issues:

1. What should be the acceptable mass and CG requirements for VAS?

This implies that there is a single shock and vibration level that can define the SOCOM acceptance criteria across the organization. While a single level may be appropriate for some SOCOM specialties, other specialties see a wide variety of shock and vibration levels depending on the mission and the mode of transportation. Riding a horse across the desert has a significantly different shock and vibration profile than riding in a fast attack vehicle. Some specialties may not be able to wear any VAS safely because of the severity of shock and vibration of their environment. AFRL has developed the concept of the "Knox" box which defines acceptable helmet CGs for a helmet weight. However, this "Knox" box varied with each ejection seat system because each system has its own acceleration profile. This suggests that different SOCOM specialties/activities may have different acceptable VAS mass and CG requirements based on the shock and vibration levels of the mission.

Future work to develop mass and CG requirements for SOCOM VAS will require defining a baseline shock and vibration environment which will define the baseline VAS mass and CG requirements. Environments that experience greater shock and vibration may need different VAS mass and CG acceptance criteria.

2. Does the addition of counterweight reduce neck fatigue?

The research is clear that fewer injuries are experienced when the helmet is lighter and closer to the CG of the human head. Improving the balance by moving VAS components to the back of the helmet, without increasing the overall weight, is an effective strategy in reducing neck fatigue and injury. However, what is less clear is if the addition of extra weight to shift the CG is also effective in reducing neck fatigue. Some research suggests it is effective, while other research suggests little improvement is achieved.

Future work in an operational-like environment is needed to determine if and how additional weight reduces neck fatigue and whether the benefits of the extra weight to shift the CG exceed its drawbacks.

8. Conclusions

VAS provide the soldier with the unique ability to see in the dark and image thermal radiation, making night operations possible and negating many types of camouflage. However, these benefits are not without drawbacks. VAS adds weight to the head and contributes to neck fatigue and injury.

This project determined the mass and CG for a number of VAS both on helmets and as stand-alone components. Seven (7) VAS were tested. Three (3) sizes of ACH and the SOCOM lightweight helmet were tested. Computational/virtual models of the helmets and VAS were also created.

Acknowledgements – We would like to acknowledge Len Ramboyong's and Bernie Corona's technical contributions to this project, Margo Mildvan for measuring the VAS and calculating the CGs, Andy Lennon for creating the EXCEL Spreadsheet that calculates the CG, and Elliot Rudie for building the computational models with mass properties of the VAS components.

9. Appendix A – Procedure for Measuring Mass and CG for VAS

9.1. Scope

This procedure measures the mass and CG of VAS when mounted on combat helmets.

9.2. Description

Mass and CG measurements of VAS are made after mounting the VAS to combat helmets such as the Advanced Combat Helmet (ACH). The helmets are secured onto standard BS EN 960:2006 headforms which are mounted to an aluminum frame CG fixture. The CG fixture sits on top of three scales, and the relative weight on each scale allows for the determination of the CG locations. (See Figure 17 below.)

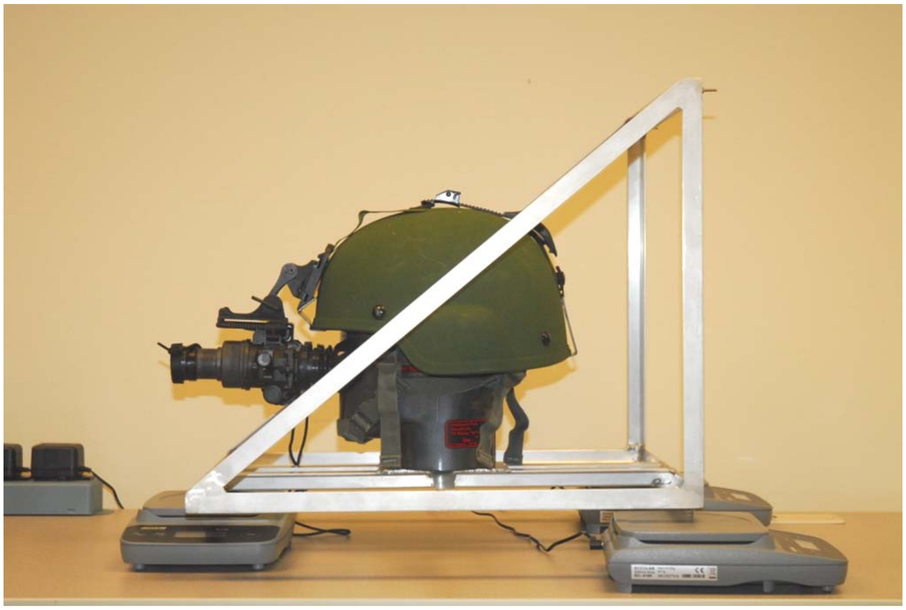


Figure 17 – CG measurement being made of VAS and Helmet.

The following procedure describes the steps involved in performing mass and CG measurements for one set of VAS. For each VAS, a complete set of CG measurements involves repeating the measurement procedure at least six times: once in the primary orientation and once in the secondary orientation for each of three helmet sizes: medium, large, and extra-large.

9.3. Referenced Documents

British Standard (BS) EN 960:2006, "Headforms for use in the testing of protective helmets," British Standards Institute.

9.4. Test Equipment and Hardware

1. 3x Digital Scales (1g or less resolution with a maximum range of at least 10kg)

2. 1x CG fixture (See Figure 3 for a drawing of the CG fixture)

3. 2x headforms (BS EN 960 Full, Urethane; Size 575 (Cadex Size J, 570mm Circumference) and 605 (Cadex Size M, 600mm Circumference), available from Cadex, Inc, 755 Avenue Montrichard, St-Jean-sur-Richelieu, Quebec J2X 5K8, Canada)

4. 2x ½-13 x 1.25” Socket Head Cap Screws

5. 2x ½” Washers

6. 1x ½” Spacer (½” tall, 3/8” diameter aluminum cylinder)

7. 3x Helmets with associated Suspension and Retention System (sizes Medium, Large, and Extra-Large)

8. VAS with associated mounts

9. Test Data Sheet (e.g. CG_RESULTS.xls)

10. CG Calculation Worksheet (e.g. Helmet RIG_CG_Console _analytic.xls)

9.5. Procedure for Measuring Mass and CG

1. Set up the three digital scales on a flat and level surface, and place the CG fixture on the scale. Each of leg of the CG fixture should rest on a scale near the center of the plate. (Use the CG fixture in the primary orientation through 16 and then repeat the steps with the CG fixture in the secondary orientation.)

2. Zero out all three scales with the CG fixture sitting on top of the scales.

3. Remove the CG fixture from the scales and mount a headform to it with two Socket Head Cap Screws and Washers. Headform “J” should be used with Medium and Large helmets, and headform “M” should be used with Extra-Large helmets (see Figure 18 for orientation of the headform)

4. Adhere the ½” Spacer to the top of the headform, at the intersection of the Transverse Plane and the Longitudinal Plane, with a double layer of two-sided Scotch tape.

5. Place the CG fixture back onto the scales, and record the weight shown on each scale into the Test Data Sheet. Ensure that the recorded weights are labeled with the respective scale #1, #2, or #3. (See Figure 18 for scale location and corresponding number.)

6. Zero out all three scales with the CG fixture sitting on top of the scales.

7. Remove the CG fixture from the scales and place it on a flat surface. Remove the crown pad from the helmet; the helmet should at this point have two Trapezoidal and four rectangular pads as well as the retention system in place. Fit the helmet onto the headform such that the helmet is on straight and the brim is parallel to the Reference Plane of the headform. Push down on the helmet to make sure it is in contact with the ½" Spacer (be careful not to bend or damage the legs on the CG fixture). Attach the chin strap and ensure that the helmet retention system is tight enough so that the helmet will not slip when the VAS is mounted onto it.

8. Place the CG fixture back onto the scales, and record the weight shown on each scale into the Test Data Sheet.

9. Remove the CG fixture from the scales and place it on a flat surface. Remove the helmet from the headform. Mount the VAS, including any mount and battery pack, to the helmet; the details of mounting the VAS will vary with each VAS.

10. Fit the helmet onto the headform such that the helmet is on straight and the brim is parallel to the Reference Plane of the headform. Push down on the helmet to make sure it is in contact with the ½" Spacer (be careful not to bend or damage the legs on the CG fixture). Attach the chin strap and ensure that the helmet retention system is tight enough so that the helmet will not slip when the VAS are mounted onto it.

11. Adjust the VAS to the down and minimum position. If the VAS is adjustable with respect to alignment to the eye, adjust it to the maximum position away from the Longitudinal Plane of the headform and to the highest position possible without hitting the brim of the helmet. If there is an angle adjustment, adjust the VAS so that it is parallel with the ground.

12. Place the CG fixture back onto the scales, and adjust the VAS to the down and maximum position. Ensure that the helmet and VAS are on straight and level. Record the weight shown on each scale into the Test Data Sheet in the appropriate row and columns.

13. Adjust the VAS to the lowered and minimum position. If the VAS bumps into the headform without reaching the minimum position, adjust the VAS as close to the minimum position as possible and make a note on the Test Data Sheet about this. Ensure that the helmet and VAS are on straight and level. Record the weight shown on each scale into the Test Data Sheet in the appropriate row and columns.

14. Adjust the VAS to the up and minimum position. Ensure that the helmet is on straight and level. Record the weight shown on each scale into the Test Data Sheet in the appropriate row and columns.

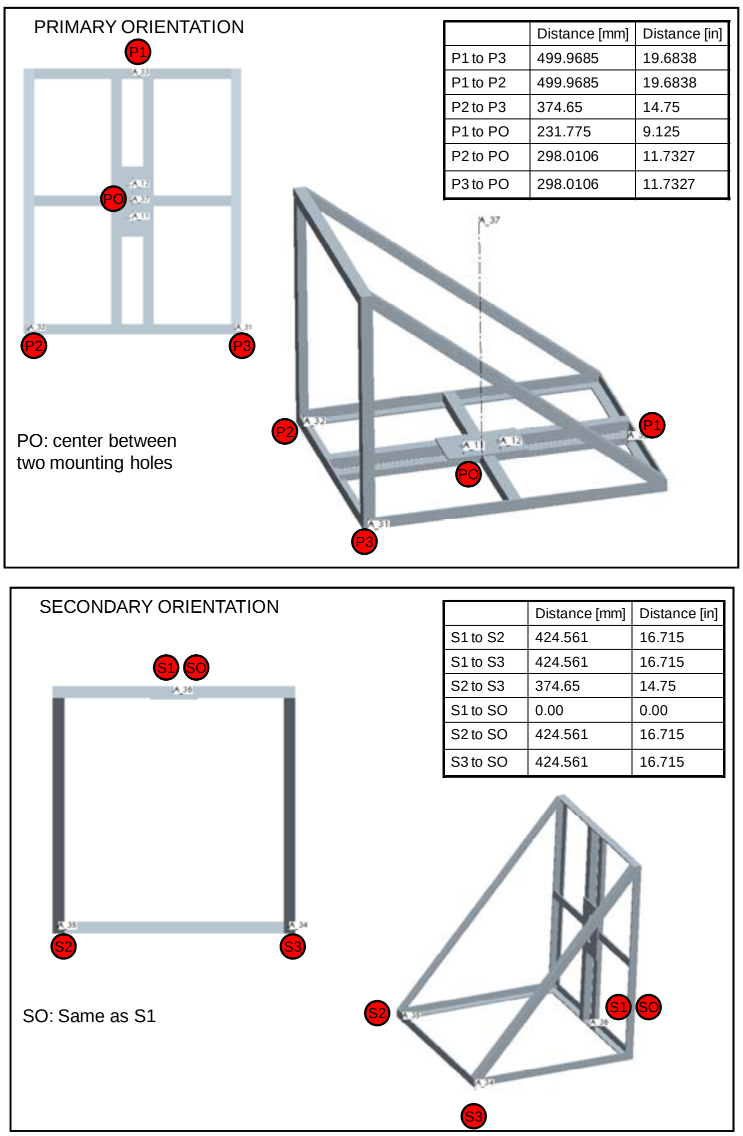
15. Adjust the VAS to the up and maximum position. Ensure that the helmet is on straight and level. Record the weight shown on each scale into the Test Data Sheet in the appropriate row and columns.

16. Remove the CG fixture from the scales and place it on a flat surface. Remove the helmet from the headform and the VAS from the helmet. Due to variances in the actual position of the helmet and VAS on the headform, steps 7 through 16 should be repeated at least twice to produce three sets of measurements.

17. Repeat Steps 1 through 16 with the CG fixture in the secondary orientation.

18. Repeat 1 through 17 with the remaining two helmets.

Measurements are complete for one VAS.



	Distance [mm]	Distance [in]
P1 to P3	499.9685	19.6838
P1 to P2	499.9685	19.6838
P2 to P3	374.65	14.75
P1 to PO	231.775	9.125
P2 to PO	298.0106	11.7327
P3 to PO	298.0106	11.7327

	Distance [mm]	Distance [in]
S1 to S2	424.561	16.715
S1 to S3	424.561	16.715
S2 to S3	374.65	14.75
S1 to SO	0.00	0.00
S2 to SO	424.561	16.715
S3 to SO	424.561	16.715

Figure 18 – Helmet CG Rig (platform) in its primary (P) and secondary (S) orientations, including actual dimensions. The references point O is the platform origin point, and the reference points 1, 2 and 3 are the locations of the stand-offs.

9.6. Calculation of Mass and CG for VAS

The following procedure describes the steps involved in calculating the mass and CG of the VAS after measurements have been completed. The process computes the mass of each component and uses a CG Calculation Worksheet to determine the location of the CG for each set of measurements based on the relative values for scales #1, #2, and #3. These CG locations are relative to the CG fixture's origin and XY coordinate system. The Test Data Sheet can be used to convert the CG locations to the headform or helmet's frame of reference, and also to determine the CG location of the VAS alone as well as the CG location of the VAS-helmet system.

Step-by-step instructions of how to perform the mass and CG calculations:

1. Enter the measured values for scales #1, #2, and #3 into the appropriate location in the CG_RESULTS.xls Test Data Sheet if not already done so. The Test Data Sheet automatically calculates the total mass for each set of measurements.

2. For each set of measurements, enter the value for scales #1, #2, and #3 into the CG Calculation Worksheet (ensure the CG Calculation Worksheet is set to the proper units of measure and proper orientation: primary or secondary). The CG Calculation Worksheet automatically calculates the CG location relative to the CG fixture's origin and XY coordinate system.

3. Transcribe these CG locations to the XY columns for "CG Distance from Frame Origin" in the CG_RESULTS.xls Test Data Sheet.

4. The Test Data Sheet automatically determines the average CG location based on the three repeat measurements of each set of tests and automatically converts the XY coordinate system locations into a XYZ coordinate system where positive-X is towards the face, positive-Y is towards the left ear, and positive-Z is towards the top of the head. Additionally, the Test Data Sheet determines the CG location with respect to the helmet's CG and to the headform's reference planes. It also provides the CG location of the VAS alone in addition to the VAS-helmet system. The Test Data Sheet also calculates the neck torque based upon the mass of the VAS-helmet system and corresponding CG location.

10. References

[1] Rash C, McLean W, Mora J, *et als*. "Design Issues for Helmet-Mounted Displays for Rotary-Wing Aviation," USAARL Report # 98-32, July 1998.
[2] McEntire BJ, Shanahan DF, "Mass Requirements for Helicopter Aircrew Helmets," USAARL Report # 98-14. January 1998.
[3] Coakwell MR, Bloswick DS, and Moser Jr R, "High-Risk Head and Neck Movements at High G and Interventions to Reduce Associated Neck Injury," *Aviat Space Environ Med*; **75**:68–80 (2004).
[4] De Loose V, Van Den Oord M, Burnotte F, *et als*. "Functional Assessment of the Cervical Spine in F-16 pilots With and Without Neck Pain," *Aviat Space Environ Med*; **80**: 477–81(2009).
[5] LaFiandra M, Harman E, Cornelius N, *et.als*. "The Effects of the Personal Armor System for Ground Troops (PASGT) and the Advanced Combat Helmet (ACH) with and without PVS-14 night Vision Goggles (NVG) on Neck Biomechanics During Dismounted soldier movements," USARIEM Technical Report T-07-09.
[6] Perry C, "Vertical testing of two helmet-mounted night vision systems," June 1994, AL/CF-SR-1994-0013, June 1994.
[7] Laporte S, Chavary E, Skalli W, Guillaume A, "Influence of Helmet Inertial Properties on Neck Injury Risk During Ejection: A Numerical Human Model Approach," Michael D. Gilchrist (ed.), IUTAM Proceedings on Impact Biomechanics: From Fundamental Insights to Applications, 139–146.
[8] Merkle AC, Kleinberger M, and Uy OM, "The Effects of Head-Supported Mass on the Risk of Neck Injury in Army Personnel," Johns Hopkins APL Technical Digest, Volume 26, Number 1 (2005).
[9] Manoogian SJ, Kennedy EA, Wilson KA, Duma SM, Alem NM, "Predicting neck injuries due to head-supported mass," *Aviat Space Environ Med* 2006; 77:509-514.
[10] Gallagher H, Caldwell E, Albery C, "Neck Muscle Fatigue Resulting from Prolonged Wear of Weighted Helmets," AFRL-RH-WP-TR-2008-0096, June 2008.
[11] Alem, NM, Meyer, MD, and Albano, JP, "Effects of Head Supported Devices on Pilot Performance during Simulated Helicopter Rides," USAARL Report No. 95-37. (1995).
[12] Barazanji, KW and Alem, NM, "Effects of Head Supported Devices on Female Aviators during Simulated Helicopter Rides," USAARL Report No. 2000-16.
[13] Butler, BP, "Helmeted head and neck dynamics under whole-body vibration," Ph.D. dissertation, University of Michigan, Ann Arbor, MI. (1992).
[14] McLean B, Shannon S, McEntire J and Armstrong S, "Counterweights Used with ANVIS," USAARL Report No. 96-30, July 1996.
[15] Knight JF, Baber C, "Neck muscle activity and perceived pain and discomfort due to variations of head load and posture," *Aviat Space Environ Med*; 75:123–31.(2004).
[16] Phillips CA, and Petrofsky JS, "Neck Muscle Loading and Fatigue: Systematic Variation of Headgear Weight and Center-of-Gravity," *Aviat Space Environ Med*; 54(10):901-905; (1983).
[17] http://www.drjrosen.com/cd134.html downloaded 9/1/09.
[18] Netter FH, *Atlas of Human Anatomy*, 4th Ed., Saunders, 2006, Plate 93.
[19] http://www.cadexinc.com downloaded 9/1/2009.
[20] Gordon, CC, *et als*. "1988 Anthropometric Survey of US Army Personnel: Methods and Summary Statistics," Natick/TR-89/044, September 1989.